NEW MILLENNIUM DS2 ELECTRONIC PACKAGING
AN ADVANCED ELECTRONIC PACKAGING "SANDBOX"

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Abstract - New Millennium Deep Space 2 (DS2) is the second project of the New Millennium Program series being managed by the Jet Propulsion Laboratory (JPL). The project consists of a pair of probes that will be carried on the cruise ring of the Mars Polar Surveyor Lander. After release from the Lander cruise stage, both probes will autonomously enter the atmosphere, gathering atmospheric and meteorological data. The probes then impact and penetrate into the Martian surface. After impact, a soil sample is taken and analyzed for the presence of water and other scientific data is recorded. Launch date is currently set at January 3, 1999.

The size and mass of the proposed probes imposed enormous constraints on the packaging of the electronics. To fit all of the required electronics within the probe envelope, the DS2 became a virtual advanced packaging experiment: Chip-on-Board (COB) is used extensively throughout the probe, which also incorporates High Density Interconnect (HDI) technology, a deployable, non-supported flexible interconnect and an highly integrated laser diode/electronics spectrometer. All of these developments represent technology "firsts" at JPL.

This paper describes the development and testing of the DS2 electronics package over the past year, including discussions on the various COB implementations, high-density surface mount applications, and the use of flexible interconnects. Additional observations regarding the integration of HDI assemblies into the probe, use of multi-purpose structure, the development of the micro-spectrometer, the use of non-Known-Good-Die and possible follow-on developments and packaging proposals for new programs at JPL will be discussed.

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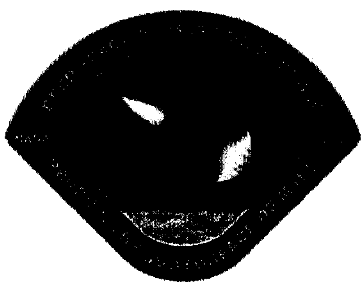
INTRODUCTION



With the recent launch of New Millennium DS1, the Jet Propulsion Laboratory is beginning to showcase its "smaller, cheaper and faster" programs. DS1 is demonstrating a number of key enabling technologies, which include the first use of an ion propulsion system, and an advanced software package. This software suite includes programs such as "Remote Agent" and "AutoNav," which autonomously handle spacecraft functions previously performed via ground command.

New Millennium DS2 is the second project of the New Millennium series. A pair of probes will be released from the cruise ring of the Mars Polar Surveyor Lander and descend autonomously into the atmosphere, gathering atmospheric and meteorological data. The probes then impact and penetrate into the Martian surface. After penetration, a soil sample is taken and analyzed for water content. Soil thermal conductivity, solar intensity and other scientific measurements are recorded.

The size (~22 sq. in. area for electronics) and total mass (< 3.5 Kg. each) of the probes impose enormous constraints on the packaging of the electronics. Fortunately, the nature of the New Millennium program encourages the use of advanced technologies to meet project goals. With this in mind, DS2 became a virtual advanced packaging experiment: Chip-on-Board (COB) was used extensively throughout the probe. A High Density Interconnect (HDI) micro-controller and COB power management electronics were purchased from industry partners. Other technology developments for this project included a deployable, non-supported flexible interconnect and an integrated tunable laser diode/electronics spectrometer. All of these developments represent technology "firsts" at JPL. The development and incorporation of these technologies into the DS2 project is the subject of this paper.

GENERAL DESCRIPTION

Figure 1 depicts the major assemblies within the New Millennium DS2, or Mars Microprobe. DS2 consists of two distinct subassemblies, the aeroshell (which is the Mars entry vehicle and shatters upon impact) and the microprobe. The microprobe itself consists of two pieces as shown in figure 2. The aftbody, which contains the telecommunications subsystem, antenna, batteries, and various atmospheric experiments, and the forebody, which contains the sample collection assembly, the optical bench and associated electronics, and an impact accelerometer. Upon impact of the planetary surface, the forebody separates from the aftbody and penetrates the Martian surface up to 1 meter in depth. The aftbody is designed to stay at or near the Martian surface, to enable the DS2 to communicate with NASA's Mars Global Surveyor spacecraft, which will be in orbit, to relay data back to Earth. A two metal layer flex-print connects the forebody to the aftbody, enabling communication between the two assemblies.

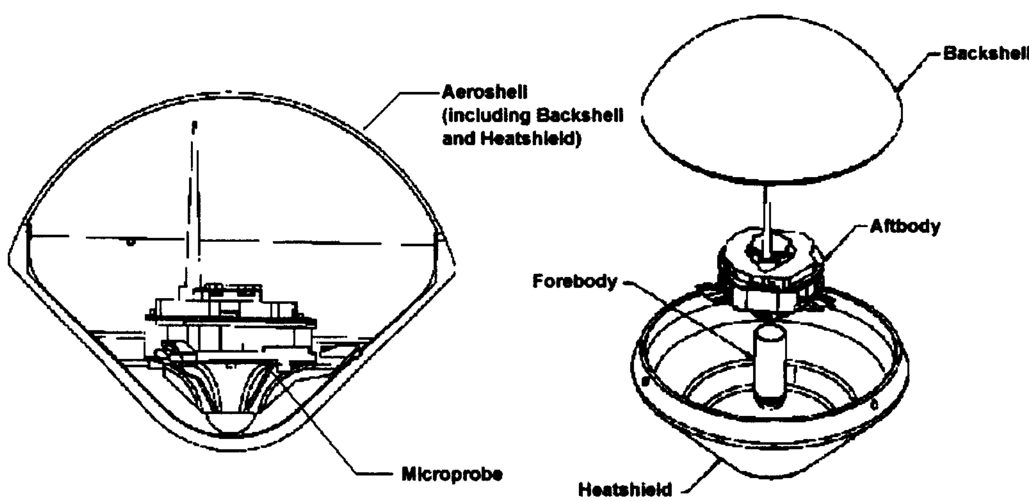


Figure 1: New Millennium DS-2 Configuration

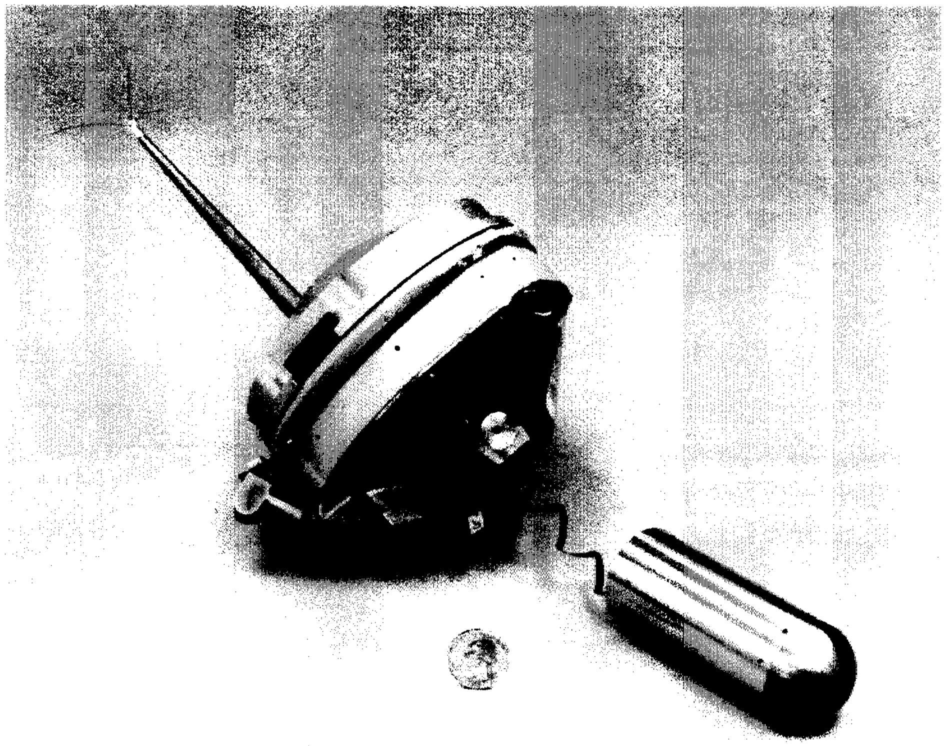


Figure 2: Microprobe Configuration

CONSTRAINTS ON DEVELOPMENT

The nature of a penetrator mission puts unusual environmental requirements on this project. The DS2 mission profile calls for an impact on the Martian surface at a probe speed of approximately 400 miles per hour. The estimated shock from this impact is 60,000 G's for the aftbody (which is designed for minimum penetration). This high shock value represents a challenge to the designers of all manner of hardware, particularly electronics.

The thermal environment is also different from previous missions, with emphasis on low temperature performance. Both the size and the mission profile for DS2 limit the amount of energy storage on the probe, precluding major power dissipation. Subsurface temperatures on Mars are estimated anywhere between 0° C to -120°C. These two factors create a thermal environment significantly colder than normally experienced by the electronics in larger spacecraft. Including prelaunch operation temperatures (up to +30° C), this leads to an environmental requirement of +30° C to -120° C for the forebody electronics assemblies. Aftbody assemblies suffer slightly less exposure, with a requirement of +30° to -80° C.

Given the unique environmental requirements posed by this project, development and testing of electronics packages concentrated in the areas of temperature excursions and impact testing. A summary of the critical environmental requirements is listed in Table 1

In addition to the unique environmental requirements, other constraints significantly shaped the DS2 mission. Cost was a major driver. The DS2 mission was conceived as a low cost mission: Total cost, including mission operations, is currently about 1/5th the budget for New Millennium DS-1, and 1/100th the budget for Cassini. As a result, funds to develop new technologies were quite limited.

A second significant constraint was time: The DS2 development schedule was quite tight. Detail design, assembly, integration and test occurred during an eighteen-month period, very quick by JPL standards. This, in conjunction with hardware development problems, led to a very compressed timetable near the end of the program.

These constraints contributed to the decision to implement a different approach to electronic packaging. This new approach, using advanced packaging technologies, permitted the electronics to be packaged more efficiently than previous missions, is described below.

Table 1. Environmental Requirements

Environment (Qualification)	Requirement
Shock	30,000 Peak g's forebody, Z-Axis 60,000 Peak g's aftbody, Z-Axis
Vibration	0.2 G^2/Hz, 40-1000 Hz
Acoustic	Maximum 132.6 dB @ 250/315 Hz
Thermal/Vacuum	+30° C to -120° C (Operating Requirement)
Thermal/Cycling	No Specific Test Requirement
Temperature/Humidity	Humidity <70% Relative Humidity (RH), No Specific Test Requirement

ELECTRONIC PACKAGING DESCRIPTION

As stated previously, the DS2 physical form factor does not permit adequate area for conventional electronics packaging. Because of this, DS2 became an advanced electronics packaging "sandbox." Many technologies that were new to JPL and would otherwise be characterized as risky were embraced because of the high-density considerations. These high-density packaging techniques are described as follows.

Highly Integrated or "Multi-functional Structure"

Utilizing the electronics support structure in a dual role often increases the volumetric efficiency of the overall package. In this case, the forebody electronics are mounted on a structure commonly known as the prism. This structure provides a load path from the front of the forebody to the science block. In addition, the prism provides six discrete areas for electronic mounting, three outer faces and three inner faces of the prism. Housed within the prism is the motor assembly, which drives the drill mechanism for sample acquisition. Figure 3 shows the prism with the enclosed motor assembly. Overall, it provides a very tight, compact package.

Chip-on-Board Variations

Early in the project development, COB was selected as the primary packaging technology to be used in the Microprobe. COB technology uses bare die on an interconnecting substrate and eliminates the die package. Environmental protection is provided by a coating or polymer encapsulation (often referred to as "glob-top"). One of the major strengths of COB technology is high density: Case studies at JPL have concluded that COB can offer up to four times the electronics density that traditional JPL packaging has allowed on previous projects.

As the development of the Microprobe progressed, it became evident that concentrating on a single COB configuration was not possible. The types of substrate materials were the major source of variation. The Boeing Defense and Space Group, one of the DS2 industry partners, could supply one type of ceramic substrate material (alumina), whereas early JPL fabricated COB utilized Low Temperature Co-fired Ceramic (LTCC). However, very late developments in the Microprobe telecommunications design did not allow time to fabricate LTCC substrates. Therefore, a decision was made to change the substrate material on these late designs. Organic substrate materials allowed for shorter fabrication lead times and had been tested in COB applications. After consideration, polyimide-glass was chosen as the substrate material, because of quick fabrication times, better temperature properties than other organic laminates, previous experience, and testing.

Other variations involved the changes needed to COB technology to withstand the worst-case impact shock. Shock testing revealed that short wire-bonds were much less susceptible to damage. To minimize wire-bond length in aftbody electronics assemblies, dies were placed in cavities on the substrate.

Environmental protection for the bare die was originally baselined as a Hysol glob-top material, supplemented with an overall Parylene coating. This configuration worked well in thermal cycling and temperature/humidity testing. However, during impact testing, it was discovered that this particular glob-top material was problematic in high-shock environments. Therefore, it was eliminated for some aftbody assemblies in favor of strictly Parylene coating, adding to the variation on COB configurations.

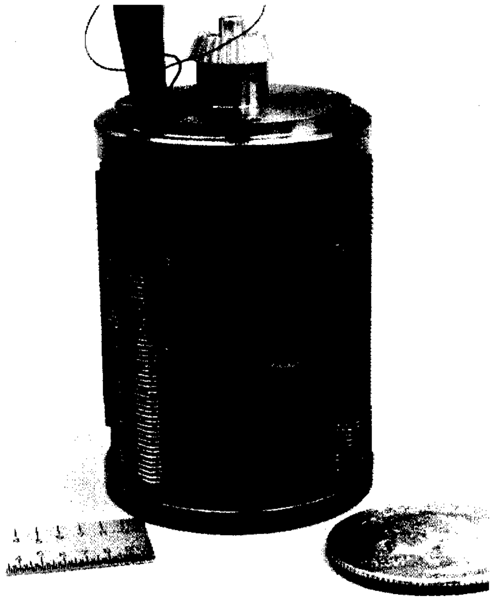


Figure 3: DS2 Prism Assembly

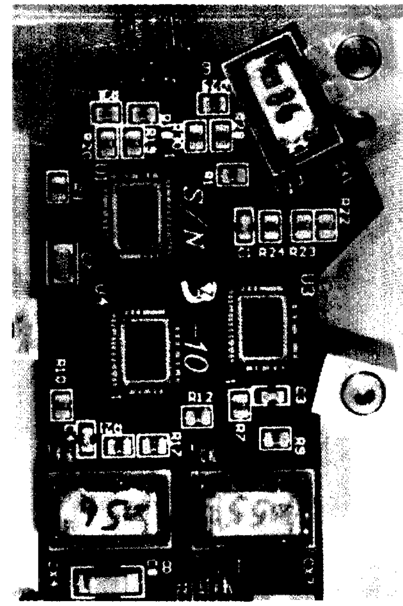


Figure 4: DS2 Aft Sensor Assembly
(Polyimide-Glass Substrate)

Ultimately, four different COB configurations made their way into the final Microprobes. These configurations are listed in Table 2. Figures 3 and 4 show two of the different COB configurations used (Figure 3 shows an LTCC substrate with Hysol Glob-top and Parylene, Figure 4 shows a polyimide-glass substrate with bare die and a Parylene coating).

Early validation testing of COB for the purpose of this project has been discussed elsewhere[1]. Further testing during the past year (powered HAST for 200 hours, new impact testing) has further qualified COB configurations for the DS2 mission.

High Density Interconnect (HDI)

The Advanced MicroController (AMC) used in DS2 is the result of a consortium led by Air Force Phillips Laboratory. This microcontroller utilizes the General Electric HDI packaging technology. HDI has been discussed in many recent journal articles[2][3][4]. This technique starts with bare die, encapsulated such that the die faces are face-up, in a single, horizontal plane. Interconnecting flex-prints are bonded to the top of this structure and via holes are laser drilled and plated, making connection between the flex-print and the die. In the case of the AMC, passive trim functions (resistors and capacitors) are mounted to the topside of the structure. This process yields a high-density, 3-dimensional packaging structure: The AMC measures approximately 20 mm wide by 30 mm tall, and is less than 2 mm thick (not including the top mounted passives), and fits snugly on one side of the forebody prism structure (see Figure 5).

Flex Interconnect

Flexible printed circuit (flex-print) was used to the maximum extent possible for interconnections between electronics assemblies. While the use of connectors would have been preferred from the standpoint of testing, disassembly, rework and assembly, size limitations would not permit their use.

Table 2: COB Configurations

Configuration No.	Substrate Material	Environmental Protection	Die Mounting
1	LTCC	Glob-top+Parylene	Surface of Substrate
2	Ceramic/Alumina	Glob-top+Parylene	Surface of Substrate
3	LTCC	Glob-top+Parylene	Cavities in Substrate
4	Polyimide/Glass	Parylene	Cavities in Substrate

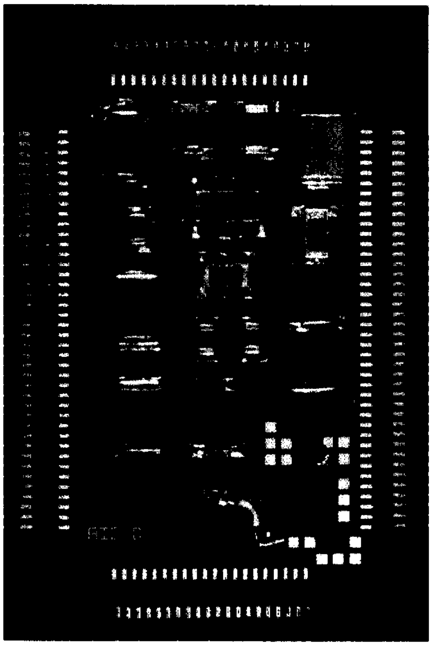


Figure 5: Advanced MicroController

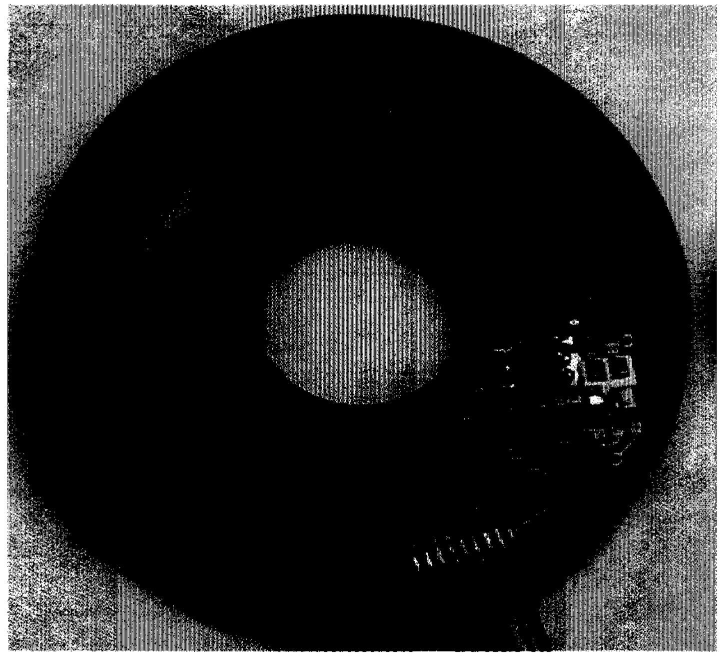


Figure 6: Water Experiment

Flex-print was used to connect all electronics assemblies on the forebody prism, the electronics assemblies to the motherboard in the aftbody, and connecting the forebody to the aftbody via a one meter umbilical flex which is deployed upon impact.

Integrated Optical/Electronics Package

The water detection system was also subject to minimal space allocation for electronics and sensors. The integration of the tunable laser diode, optics and the front-end electronics decreased the size of the overall instrument to fit into the allocated area.

The final designed configuration was essentially a spectrometer optical bench on a printed wiring board. A path for water vapor from a heated sample is directed through a hole in the printed wiring board. A light emitting diode (LED) laser tuned to a water spectrum line passes through the vapor path, is bounced off a small mirror (to increase the optical path) to a detector. The relative intensity of the signal is measured by the detector and reduced to determine whether water exists in the sample.

Figure 6 is a photograph of the printed wiring board, including the MEMS laser, focusing lens, mirror, detector and front-end electronics. This printed wiring board integrates optical elements, COB, and plastic encapsulated packages all into a single, small package.

High Density Surface Mount Technology

Lastly, lack of availability of specific bare die for Radio Frequency (RF) portions of the Microprobe led to the use of Surface Mount Technology (SMT) for the probe Transceiver Assembly. Originally envisioned as a mixed signal Application Specific Integrated Circuit (ASIC) function, the available area for the transceiver was very tight, necessitating one of the highest density SMT designs to be fabricated and assembled at JPL. A total of 292 components were packaged into an area of less than five square inches (see Figure 7). Even with this packaging effort, the transceiver utilized all remaining electronics real estate on the probe aftbody, and required the elimination of some science electronics to "shoe-horn" everything in.

As can be ascertained from the previous discussions, a number of innovative packaging techniques were used in the design and assembly of the Microprobes. These new technologies were not incorporated without unexpected and unforeseen problems and difficulties. Solutions to these problems and the lessons learned give the best insight into integration of new technologies for future missions.

LESSONS LEARNED

The major portion of the detail design, development, assembly and testing of the two DS2 Microprobes took place over the past 18 months, with final delivery to Cape Canaveral occurring on 10 November 1998. For a JPL project, this is a very short development schedule, particularly with the number of new technologies being implemented. To add to the schedule problems, the design completion of the telecommunications system did not occur until October 1998. This led to a very late completion of the Telecom assemblies and subsequent, two and three shift assembly and test operations, to keep the Microprobes on schedule.

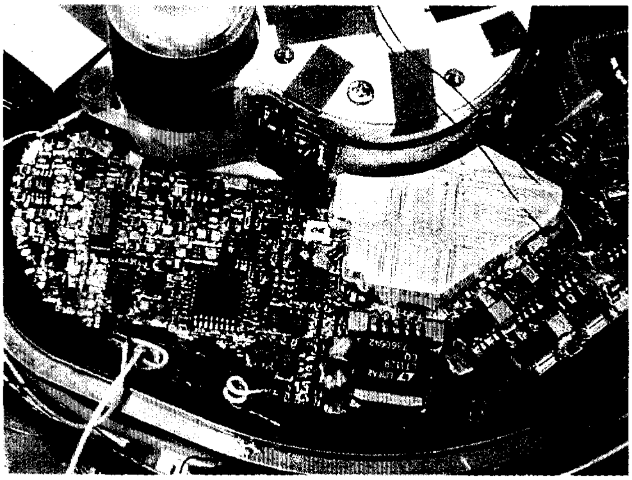


Figure 7: DS2 Transceiver Assembly

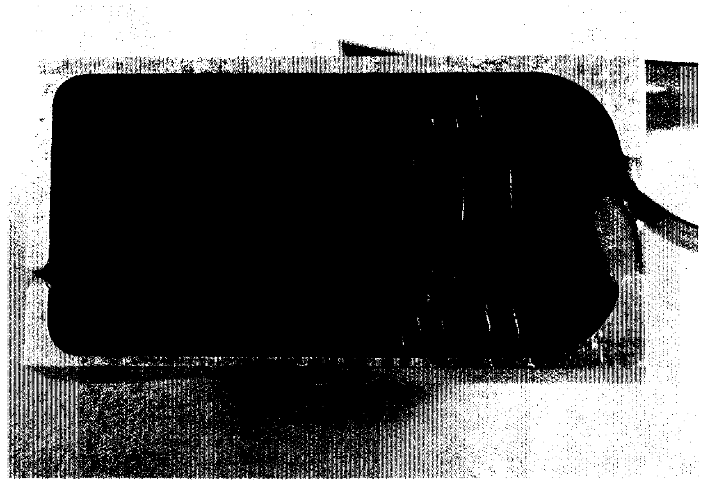


Figure 8: Stowed DS2 Umbilical Flex

As a result of this accelerated schedule and new technology implementation, problems arising from new technology incorporation were resolved quickly and occasionally, limited or sub-optimal solutions were utilized. Better solutions to these problems will be needed by future projects. These particular problems, along with some of the packaging lessons learned of the DS2 project, are discussed below.

Live Testing, Performed Frequently

To gain insight into how COB technology would perform in high-G environments, early test samples were impact tested to simulate the 60,000 G expected environment. To minimize costs and development time, these early test samples were mechanical samples only. Visual inspection of these assemblies was performed after impact testing, and the glob-top appeared to be undamaged.

Testing during the past year was performed on electrically functioning assemblies, in which bare die were mounted to polyimide-glass printed wiring boards (without cavities for the dies), wire-bonded and glob-topped. Impact testing of these assemblies yielded different and somewhat disturbing results. After impact, these assemblies visually appeared to be undamaged. However, electrical function was compromised: out of three test circuits, only one functioned normally. One test circuit behaved erratically and changed behavior when pressure was applied to the glob-top. The last test circuit did not function at all.

Closer visual examination revealed fine cracks in the glob-top material, undetected in previous inspections. New impact tests were conducted using the same test assembly, but with the die mounted in cavities in the printed wiring board. While the test circuits still functioned after testing, similar cracks in the glob-top were noted.

Ultimately, flight assemblies were configured with die in printed wiring board cavities with no glob-top. Parylene coating served as the environmental protection for these assemblies. This configuration successfully passed impact tests and temperature/humidity tests. Unfortunately the wire-bonds are exposed to mechanical damage during handling and assembly operations. Temporary covers were used to protect exposed wire-bonds. Once these covers were removed (late in the assembly phases of the probe), great care was necessary to prevent damage.

The lesson learned here is clear: Test early, test often, and test live.

3-D Structures Need Advanced Testing and Evaluation Tools

The Advanced MicroController, supplied by the Phillips Laboratory led consortium, functioned well given the limited development time afforded by the project schedule. However, one specific unit developed a problem during temperature testing: accessing the onboard memory became problematic over temperature. The problem was isolated to a memory die or it's interconnecting structure. Pinpointing the problem further proved difficult, since the product of the HDI process is essentially an encapsulated unit, with very little visibility to internal structures. To date, real time (Fein-Focus) X-rays and destructive analysis (cross-sectioning) have been considered and ruled out because of the low chance of success in finding the problem source, and the limited availability of AMCs.

Traditional projects would have spent much more time, money, and effort locating this problem, since some of the possible fault conditions could have been generic, affecting the entire AMC lot. This problem points to the need for more sophisticated diagnostic techniques when dealing with 3-dimensional packaging structures such as HDI.

Sometimes You Can Bend the Rules

The Umbilical Flex was conceived as the method for interconnecting the forebody to aftbody on the Microprobe, deploying "fire-hose" style up to one meter (expected distance between the forebody and aftbody) after impact. However, as the design progressed, it became apparent that some of the traditional rules of flex-print would have to be stretched in order to package the umbilical in the stowed condition.

Military specifications[5] call for a minimum 10x – 30x bend radius for flex-print. Given the eventual volume allocated for this function, it was determined that a bend radius of 4x – 6x would be required to stow 1 meter of flex-print. A simple, two-sided flex-print was designed, using an adhesiveless polyimide/copper laminate, with an overall thickness of approximately 0.17 mm. A number of different bending methods and tooling were tried, and the flex was successfully bent and stowed (see Figure 8). This flex has been impact tested, and also survived multiple bend/unbend cycles in the lab.

It is interesting to note that an additional layer of thin, 3 micron thick copper (envisioned as a EMI shield) was added to both sides of the flex at one point during the development cycle. The bend characteristics of this flex proved to be completely different, with 3x - 6x bends damaging both external copper and internal traces. Further electrical testing eliminated the need for this external shield, and it was deleted from the flight design.

How Risky is Not Known Good Die?

Given its fiscal constraints, DS2 could not afford known good die. Dies purchased for this project were from commercially available lots, and came from mature fabrication lines. The dies were probably wafer probed, but this was not specifically requested in the procurement documentation.

With all of the discussions in recent papers regarding the costs and ultimate value of known good die, this policy was originally viewed with some skepticism. However, after all the fabrication and assembly efforts were completed, it was apparent that die failures were a very small problem: Greater than 95% of the die operated satisfactorily through all test phases of the Microprobes (including the spare units).

Micro-Spacecraft Will Require a Different Skill Set for Assembly Operations

During early planning phases of the DS2 project, it became apparent that the Microprobe assembly was unlike any other prior space projects at JPL. The use of small (2-56 and 0-80) fasteners, epoxy bonding near critically delicate objects, and exposed COB assemblies all required a level of precision and dexterity not normally required.

To expedite assembly operations, while maintaining the safety of all hardware, hybrid microelectronic technicians were used in all phases of the DS2 assembly (see Figure 9). In addition, in spite of the test results received from glob-top sealants for COB assemblies, it was decided that the Microprobes should be placed in nitrogen storage when not actively in assembly operations. The entire assembly process was a change from previous efforts.

In this respect, we view DS2 as a vanguard of the way new generation spacecraft will likely be assembled. Three story high bays will no longer be required: They will be replaced by smaller, class 10,000 (or cleaner) microelectronics assembly areas.

Figure 9: Final Assembly Operations

SUMMARY AND FUTURE WORK

It is not often that so many new technologies are incorporated into one project, particularly one as small and fiscally constrained as New Millennium DS2. DS2 became essentially an advanced electronic packaging "sandbox," a test vehicle for new packaging ideas for the DS2 packaging team. Lessons learned on this project will pave the way for future, smaller spacecraft using COB technology and HDI packaged products.

Work required in the immediate future will center in two areas. The first area is the qualification of COB technology for higher visibility, low-risk missions. The DS2 Microprobes were fabricated and assembled in less than 12 months and were frequently stored in nitrogen environments. Environmental protection for the die (glob-top and Parylene) was judged adequate for this application. COB technology qualification for these Class "A" (low risk) projects will require more testing, particularly in the area of thermal cycling and temperature/humidity to further bound the process and process limits.

Further validation of a variety of COB technology processes and configurations is the second area of future work. To accomplish this, a program funded by NASA code AE is developing a novel test assembly, which uses Built-In Self Test protocols to electrically monitor die functionality during environmental testing. Using Taguchi design of experiments techniques, a number of substrates, environmental protection schemes and processes will be tested to determine performance in different environments[6].

Given the insight and experience gained in DS2, there is tremendous optimism that this future work will demonstrate that COB technology (and other advanced packaging techniques) is suitable for a variety of future applications. Given the eventual research and general qualification, these advanced packaging technologies have the promise of changing the shape (and size) of the upcoming NASA missions.

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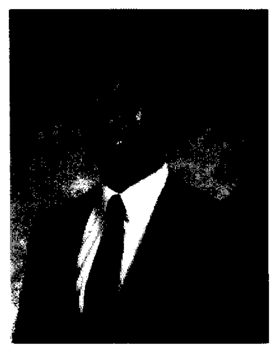
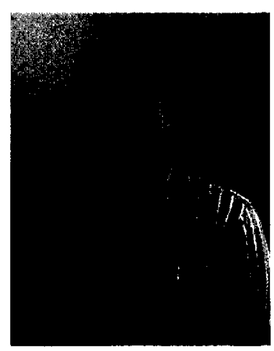
BIOGRAPHIES



Genji A. Arakaki received his Bachelor's degree from Occidental College and his Masters degree from the University of California at Los Angeles, both in Physics. He has been employed by the Jet Propulsion Laboratory since 1978. He is currently the supervisor of JPL's Advanced Electronic Packaging Group. Prior to this assignment, Genji was the technical manager of electronic packaging for NASA's Cassini Project.



Saverio D'Agostino, graduated from The University of Illinois, Champaign/Urbana in 1970 with a B.S. in Metallurgical Engineering. His career began at a Navy Materials Laboratory in Crane Indiana studying thin-film structures, electromigration and supporting the Navy's "captive" ASIC fabrication lines with process control and failure analysis. He left Crane as Manager of the Engineering Materials Branch and joined the Materials Applications Group at JPL in 1979. While there he worked as the Materials Engineer on Wide Field and Planetary Camera and the Galileo Spacecraft structure and RPM. From '83 to '93 he was Technical Section Head of the Advanced Packaging Section at Hughes Missile Systems and developed patented designs for stacked and high-G (100,000 Gs), chip-on-board electronics. Upon *returning to JPL in 1993, he was the packaging engineer for the MISR instrument and then Task Leader for Direct Chip Attachment in NASA's Advanced Interconnect Program. He is currently also the Electronic Packaging Lead for the Mars Microprobe Project, which incorporates COB electronics tightly integrated into its structure for high-G survivability and high-volume efficiency.*